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AD NUMBER
AD007720
CLASSIFICATION CHANGES
TO: **unclassified**
FROM: **confidential**
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; DEC 1952. Other requests shall be referred to Bureau of Ships (Navy), Washington, DC.**
AUTHORITY
BUSHIPS ltr, 26 Mar 1959; NAVEXOS ltr, 1 Apr 1968

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SPERRY GYROSCOPE COMPANY
DIVISION OF THE SPERRY CORPORATION
GREAT NECK, NEW YORK

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SEVENTH INTERIM DEVELOPMENT REPORT
ON
STUDY OF TECHNIQUES FOR MEASURING MICROWAVE HIGH POWER BREAKDOWN IN WAVEGUIDE TRANSMISSION LINES

THIS REPORT COVERS THE PERIOD SEPTEMBER 1, 1952 TO NOVEMBER 31, 1952

SPERRY GYROSCOPE COMPANY
DIVISION OF THE SPERRY CORPORATION
GREAT NECK, NEW YORK

NAVY DEPARTMENT, BUREAU OF SHIPS, ELECTRONICS DIVISION
CONTRACT NObsr-52227, INDEX NO. NE-110607

SPERRY REPORT
NO. 5224-1318

COPY NO. 3
DECEMBER 1952

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This report contains 19 pages and 5 illustrations.

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ABSTRACT

A series of tests was run to determine the effect of external irradiation upon breakdown. These tests indicate that irradiation with one millicurie of Cobalt-60 has no effect upon breakdown.

Data is presented on breakdown power vs. pressure for a 1" x 1/2" waveguide. In the range of pressures between 1/6 and 1/2 atmospheres, the power is proportional to the square of the pressure.

Tests are described wherein the pulse width was varied and the duty cycle maintained relatively constant. The results show that the breakdown power increases about 30 o/o as the pulse width is changed from 2.35 to 0.8 μsec.

On the basis of the data, the breakdown power of a 1" x 1/2" waveguide was computed to be 1.2 megw at atmospheric pressure for a pulse width of 2.35 μsec and a repetition rate of 400 pps.

PART I

SECTION A

PURPOSE

1. PURPOSE OF DEVELOPMENT

This contract is primarily concerned with the development of a measurement technique to determine waveguide peak-power-carrying capacity as a function of several electrical and mechanical variables. A secondary purpose involves the determination of the peak-power capacity of specified components in 1.000 x 0.500-inch waveguide.

2. STUDY AND WORK PHASES

The course of the program is such that the following points will be particularly stressed:

a. Study and full appraisal of all presently available technical information on the subject of breakdown in waveguide transmission lines and components.

b. Study and experimental investigation of various means for the positive measurement of peak-power capacity.

c. Development of the techniques required for the application of the method of measurement chosen from b.

d. Investigation into the problem of determining the breakdown region.

e. Application of the results of the previously described work to an investigation of the dependence of peak-power capacity upon the following design parameters:

(1) pulse duration
(2) pulse shape
(3) pulse repetition frequency
(4) gas pressure
(5) nature of the gas
(6) mechanical finish
(7) plating material
(8) microwave frequency

f. The 1.000 x 0.500-inch waveguide components to be tested shall include the following:

(1) DA-22/U Termination
(2) CU-206/U Directional Coupler
(3) CU-164/U Interlocked Flexible Waveguide
(4) CU-168/U Convoluted Flexible Waveguide
(5) UG-446/U Waveguide to Type-N Adapter
(6) UG-456/U Series Tee
(7) UG-457/U Shunt Tee
(8) UG-39/U Flange-to-Choke Joint

(9) UG-39/U Flange-to-Flange Joint

(10) Rotating Joint, Circular-Waveguide Type

(11) Rotating Joint, Rectangular-Waveguide Type

(12) Directional Coupler, Branch-Guide, 10-db

(13) Directional Coupler, Two-Hole, 20-db

(14) Directional Coupler, Bethe-Hole, 25-db

(15) Directional Coupler, Long-Slot, 10-db

(16) Directional Coupler, Schwinger, 30-db

(17) Waveguide Switch, Rotating-Drive Type

(18) Waveguide Switch, Resonant-Ring Type

(19) Waveguide Switch, Rotating-Disc Type

(20) Rat-Race Duplexer

(21) Conventional Waveguide Duplexer

SECTION B

DETAIL FACTUAL DATA

3. INTRODUCTION

The survey of all presently available technical information on the subject of breakdown has been completed. The experimental phase of the work is now well under way. Tests are being made using reduced pressure to induce breakdown. The circuit employs a Transvar* Coupler to suppress harmonics, a thermistor mount to measure the power, and a photocell to detect breakdown. This circuit is consistent with the statistical approach which was proposed on a theoretical basis and later experimentally verified.

As stated in the sixth quarterly report, the region of breakdown was located using photographic paper. This served to establish the swayback-type section of a 1" x 1/2" waveguide as the breakdown region and accordingly breakdown tests were initiated using this test piece. It was decided that it would be significant to determine first the effect of external irradiation upon breakdown. This would provide a check against the results of previous experiments. In addition, if the effect could be determined, it would greatly simplify future testing.

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* Trade Mark

The source chosen for this work is an irradiated cobalt-60 wire which is hermetically sealed in a steel rod. The source strength is approximately one millicurie, and the radiation consists of equivalent amounts of two gamma rays of 1.1 and 1.3 MEV. This source was chosen because it is easily obtained, easily handled, requires few safety precautions, and is adequate for the job.

In the tests that follow the value given for the breakdown power is that which corresponds to the minimum sparking probability. This value has been referred to as the onset stress in previous reports. A complete probability curve was not taken for two reasons. First, breakdown in the test section traveled back to the pressure window and caused continuous breakdown at this point. This made it impossible to count the number of breakdowns in the test section. Second, a complete probability run at each point would considerably lengthen the test time and thus would limit the useful data.

4. EFFECT OF IRRADIATION

The effect of external irradiation on the breakdown section at the breakdown power was determined from a series of tests employing varying amounts of irradiation. This was accomplished by setting the cobalt at several fixed distances from the waveguide and measuring the breakdown power as a function of the gas pressure.

The procedure adopted was to set the magnetron output at a value near its rated maximum. Referring to figure 1, the phase shifter was then adjusted to produce a convenient power level in the test section. The pressure in the test section was reduced in small increments until breakdown occurred, as noted by the photocell and electronic counter. This reading was then checked and the process was repeated for other power levels.

TABLE 1

BREAKDOWN WITH COBALT IN CONTACT WITH WAVEGUIDE

Bridge Reading (Milliwatts)	Average Power (Watts)	Gauge Pressure (Inches of Hg)	Absolute Pressure (Inches of Hg)	Time (Min)	Breakdown Occurred
60	150	18.6	11.4	5	no
60	150	19.0	11.0	5	no
60	150	19.1	10.9	0	yes
60	150	18.6	11.4	5	no
60	150	19.0	11.0	10	no
60	150	19.1	10.9	1/4	yes

This procedure was repeated for the cases with the cobalt in contact with the waveguide and also at one- and two-inch intervals from the waveguide wall. A typical set of data is given in table 1, and the complete test results are shown in figures 2, 3, and 4. It should be noted that the average power is used as the abscissa. Since the magnetron was operated at the same power level in all the tests, this makes the curves self-consistent and eliminates errors due to pulse shape and repetition-rate measurements.

A comparison of figures 2, 3, and 4 shows that for power levels above 80 watts the curves are approximately colinear. This indicates that for powers between 80 and 200 watts, and pressures between 7 and 13 inches of mercury, a variation in intensity of irradiation produces no change in breakdown power. The magnitude of this variation can be approximated since the geometry of the cobalt is known and the intensity varies inversely as the square of the distance from the source. This is not necessary, however, since another test was run using no external irradiation. This data is shown in figure 5 wherein the indicated points refer to breakdown with irradiation and the solid curve represents breakdown with the cobalt in contact with the waveguide. In this connection it should be noted that the solid curve is hot a reproduction of the data of figure 2. The difference between the two curves is that the data was taken with two different magnetrons..

As shown in figure 5, the breakdown power without irradiation was never lower than was obtained at the same pressure with irradiation, which is consistent with normal expectation. In general, without irradiation the breakdown power was about 20% higher than that under the same conditions with irradiation. However, it should be observed that there are two points which coincide with the line, which indicates the irradiation did not lower the breakdown power. These points were obtained by waiting for a period of one hour before breakdown occurred without irradiation, whereas most of the other points were obtained using a 10-minute interval. The normal waiting period with irradiation was 5 minutes and breakdown usually occurred after a wait of several minutes. Since the number of available electrons with the cobalt is of the order of 10^6 times that otherwise present, it is seen that the probability of breakdown in an hour without cobalt is considerably less than the probability in 5 minutes with cobalt This would explain the fact that the breakdown power without cobalt was generally higher.

It must be mentioned at this point that several other runs were made wherein the power was held constant for one hour with no external irradiation. After no breakdown was observed the cobalt was introduced and breakdown resulted. This is not surprising in view of the number of electrons available.

Considering figures 2, 3, 4, and 5 it may be said with a good degree of certainty that external irradiation does not lower the breakdown power. The results are not conclusive for several reasons. First, it is impossible to achieve the same probability of breakdown with no external irradiation as a waiting period of about 10^6 x 5 minutes, or about 10 years would be required. Second, figures 3, 4, and 5 are not uniform over the entire range. Since figure 2 is linear over the entire range, this casts some doubt as to the accuracy of the measurements at lower power and pressure. Fortunately, there is good agreement at the high-pressure end which is closest to the normal operating range of atmospheric and higher pressures.

5. BREAKDOWN POWER AS A FUNCTION OF PRESSURE

All of the data presented so far has been in the form of curves of breakdown power vs. pressure. Except for the investigation into the effect of irradiation, the pressure has been the only parameter varied. Since it is intended that these power-pressure curves be extrapolated to determine breakdown under atmospheric conditions, it is necessary to examine these curves critically to check the validity of such a method.

As shown by the data, figure 2 is linear over its entire range and figures 3,4, and 5 are linear for higher power and pressure. If it is assumed that the linear region is more reliable, then it is estabilished that the logarithm of power versus the logarithm of pressure is a straight line. As shown below, this means that the breakdown power is a function of the pressure raised to some power. First, assume

$$\text{power} = \text{constant} \times \text{pressure}^{\text{exponent}}$$

$$\text{or, } P = Kp^{n}$$

$$\text{then } \ln P = \ln K = n \ln p$$

$$\text{slope of } \ln P \text{ vs. } \ln p = \frac{\ln P1 - \ln P2}{\ln p_1 - \ln p_2}$$

$$\text{slope} = \frac{\ln K + n \ln p_1 - \ln K - n \ln p_2}{\ln p_1 - \ln p_2}$$

$$\text{slope} = n$$

Therefore, if the curve of ln power vs. ln pressure is linear, then the slope of the curve is the exponent to which the pressure must be raised. This exponent varies from a maximum of 2.08 in figure 2 to a minimum of 1.84 in figure 3; the mean is 1.95. For breakdown under low-frequency conditions, the corresponding value is 2, which is arrived at by a consideration of Paschen's Law. This Law states that the breakdown voltage is a unique function of pressure times the gap width. Since the voltage is approximately proportional to the gap width, this means that the breakdown voltage is very nearly directly proportional to the pressure. As a consequence, the breakdown power is proportional to the square of the pressure and the exponent is 2.

The close agreement between the mean value of 1.95 and the low-frequency value of 2 is gratifying. First, this provides a check on the accuracy of the measurements. And second, it justifies the extrapolation of the data to higher values of pressure.

6. EFFECT OF PULSE WIDTH

Tests were made to determine the effect of a change of pulse width and repetition rate upon breakdown. The results are shown in figures 5, 6, 7, and 8. Figures 6 and 7 also indicate that the power is approximately proportional to the square of the pressure since the slopes are 2.08 and 1.90 respectively. Figure 8 shows the data of figures 6 and 7 normalized to take account of the different duty cycles for the three tests. For this purpose the 0.0096 duty cycle of the 1.2 μsec pulse and 800 pps test, shown in figure 5, was taken as the standard.

Qualitatively, figure 8 shows that the power carrying capacity decreases as the pulse width is increased from 0.8 to 2.35 μsec. This may be explained on the basis of the time required to form the spark. At the smaller values of pulse width it is more difficult to complete the process during the time the power is available and therefore breakdown occurs at a higher power level. Another factor to be considered is that for the smaller pulse widths the pulse is less rectangular in shape. This would further decrease the time during which the peak power is available as compared to the total pulse width.

Quantitatively, the breakdown power for the 1.2 μsec pulse is about 15% higher than for the 2.35 μsec pulse. It is impossible on the basis of this limited data to draw any conclusions; however, a comparison may be made between this data and that reported by MIT*. This data shows that at a repetition rate of 500 pps the relative breakdown powers were 1.00, 1.17, and 1.29 for pulse widths of 2, 1.2, and 0.8 μsec. This approximates the results shown in figure 8.

It should be noted at this point that the entire effect shown in figure 8 cannot be attributed to the change in pulse width. The repetition rate was also changed, the values being 400, 800 and 1000 pps. According to the data presented in the MIT report, the breakdown power is a linear

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* MIT Radiation Laboratory Report No. 731

function of (K-R), where K is a constant and R is the repetition rate. For this frequency range K is 8000, so that the effect of this change is about 10% in the extreme case. On a theoretical basis one might expect no change in breakdown power with repetition rate, since a higher repetition rate merely serves to provide more chances for breakdown which should increase the probability but should not lower the power. This assumes, however, that there is no mutual effect between pulses. If, on the other hand, one pulse does affect the next, then the time between pulses can affect the breakdown power. In this fashion the breakdown power would decrease with an increase in repetition rate. At this time there is insufficient data to draw any conclusions regarding this effect.

7. BREAKDOWN OF A 1" x 1/2" WAVEGUIDE AT ATMOSPHERIC PRESSURE

The data of figure 8 is sufficiently uniform and consistent to permit an extrapolation to values of higher pressure. This extrapolation will be made on the basis of a square-law relationship between power and pressure. This value is used because it is very close to the average value of the exponent, 1.96, obtained from all the runs. In addition, there is theoretical justification for a square-law relationship based upon an extension of Paschen's Law. The point to be used as a basis for the extrapolation is the high-power point obtained in the run using a 2.35 μsec pulse. This point was chosen because it represents the highest pressure of all the tests, which reduces the amount of extrapolation. In addition, the longer pulse is probably the most rectangular in shape.

The values at this point are:

Average power	= 232w
Absolute pressure	= 14.1 inches of H_g
Pulse width	= 2.35 μsec
Repetition rate	= 400 pps
VSWR	= 1.08
Frequency	= 9375 mc

At atmospheric pressure and with a matched termination, the peak-power-carrying capacity of a 1" x 1/2" waveguide is:

Peak-power-carrying capacity =

$$(\text{average power}) \times \left[\frac{\text{atmospheric pressure}}{\text{test pressure}}\right]^2 \times \frac{K^2}{(\text{repetition rate} \times \text{pulse width})}$$

where $K = \dfrac{\text{peak voltage under test conditions}}{\text{peak voltage for matched condition}}$

$$P = 232 \times \left(\frac{30}{14.1}\right)^2 \times \frac{(1.04)^2}{400 \times 2.35 \times 10^{-6}} = 1.21 \text{ megw}$$

The value given by the MIT report for breakdown under these conditions is 1.1 megw which is obtained by extrapolation of data for breakdown of a section of reduced height.

The close agreement between these two values provides a good cross-check on both systems of measurement.

SECTION C

CONCLUSIONS

8. GENERAL CONCLUSIONS

Tests were conducted to determine the effect of external irradiation upon the power-carrying capacity of waveguides. It was shown that the use of 1 millicurie of radioactive cobalt increases the probability of breakdown, but does not lower the minimum power required for breakdown.

Additional measurements were made of the variation of breakdown power with pressure. In these tests the pressure was varied between 1/6 and 1/2 atmosphere and radioactive cobalt was employed. The data indicates that for this range of pressure the breakdown power is proportional to the square of the pressure.

The effect of a variation in pulse width was also qualitatively determined. The data indicates that a change from 0.8 to 1.2 to 2.35 μsec produces decrements of 15% each in the power-handling capacity of a 1" x 1/2" waveguide.

The maximum power-handling capacity of a 1" x 1/2" waveguide was computed to be 1.2 megw. This value applies for the following conditions:

Pressure	=	atmospheric
Pulse width	=	2.35 μsec
Repetition rate	=	400 pps
VSWR	=	1.00
Frequency	=	9375 mc

This value was obtained by extrapolation of data from one-half atmosphere on the assumption of the power being proportional to the square of the pressure.

PART II

PROGRAM FOR THE NEXT INTERVAL

9. PROGRAM FOR THE EIGHTH QUARTER

Testing of the required components will begin during the next interval. These tests will be conducted so that additional information on the effect of pressure, pulse width, and repetition rate will be obtained as well as the breakdown power.

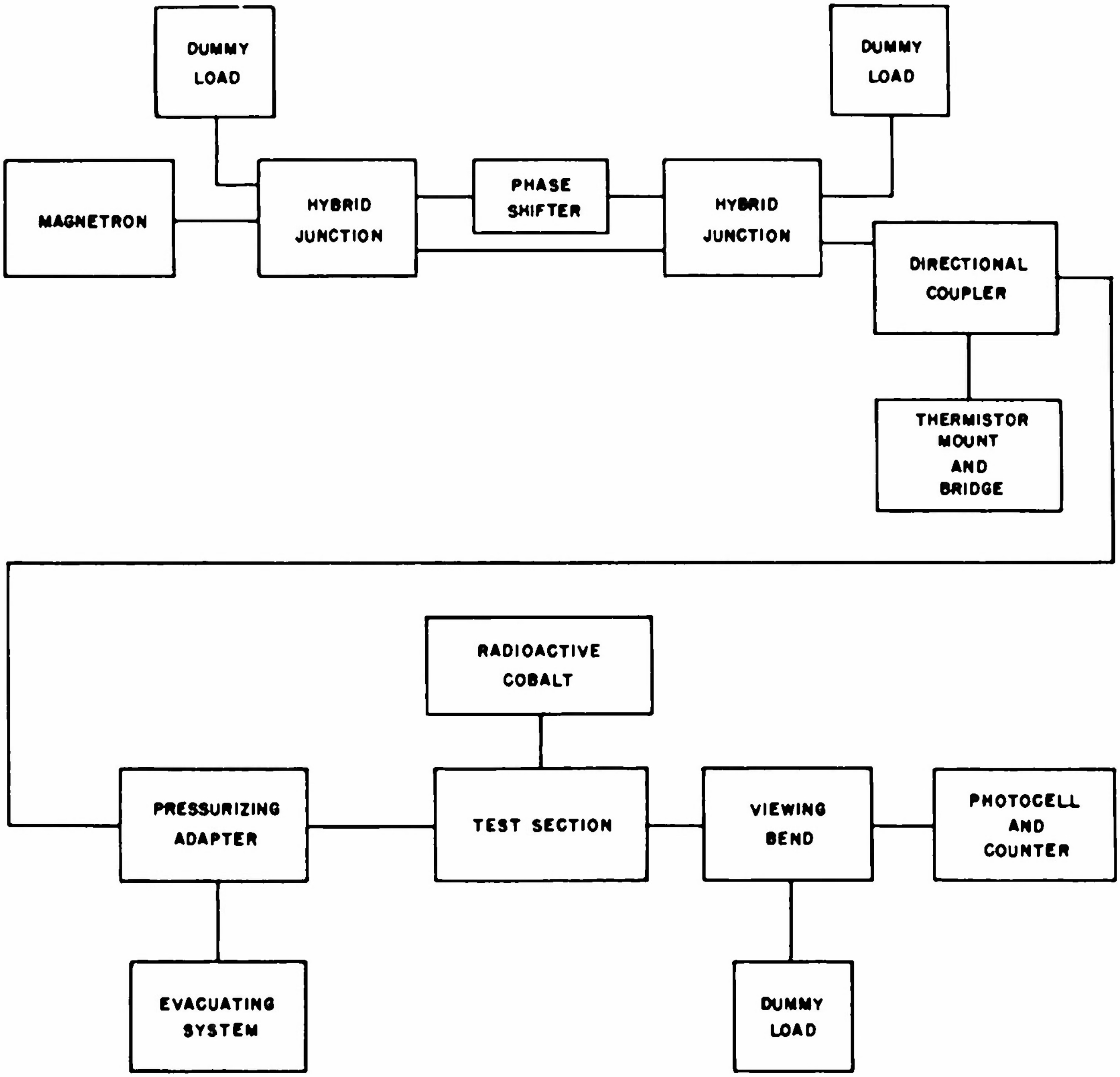

FIGURE I
BASIC CIRCUIT FOR
POWER vs. PRESSURE TESTS

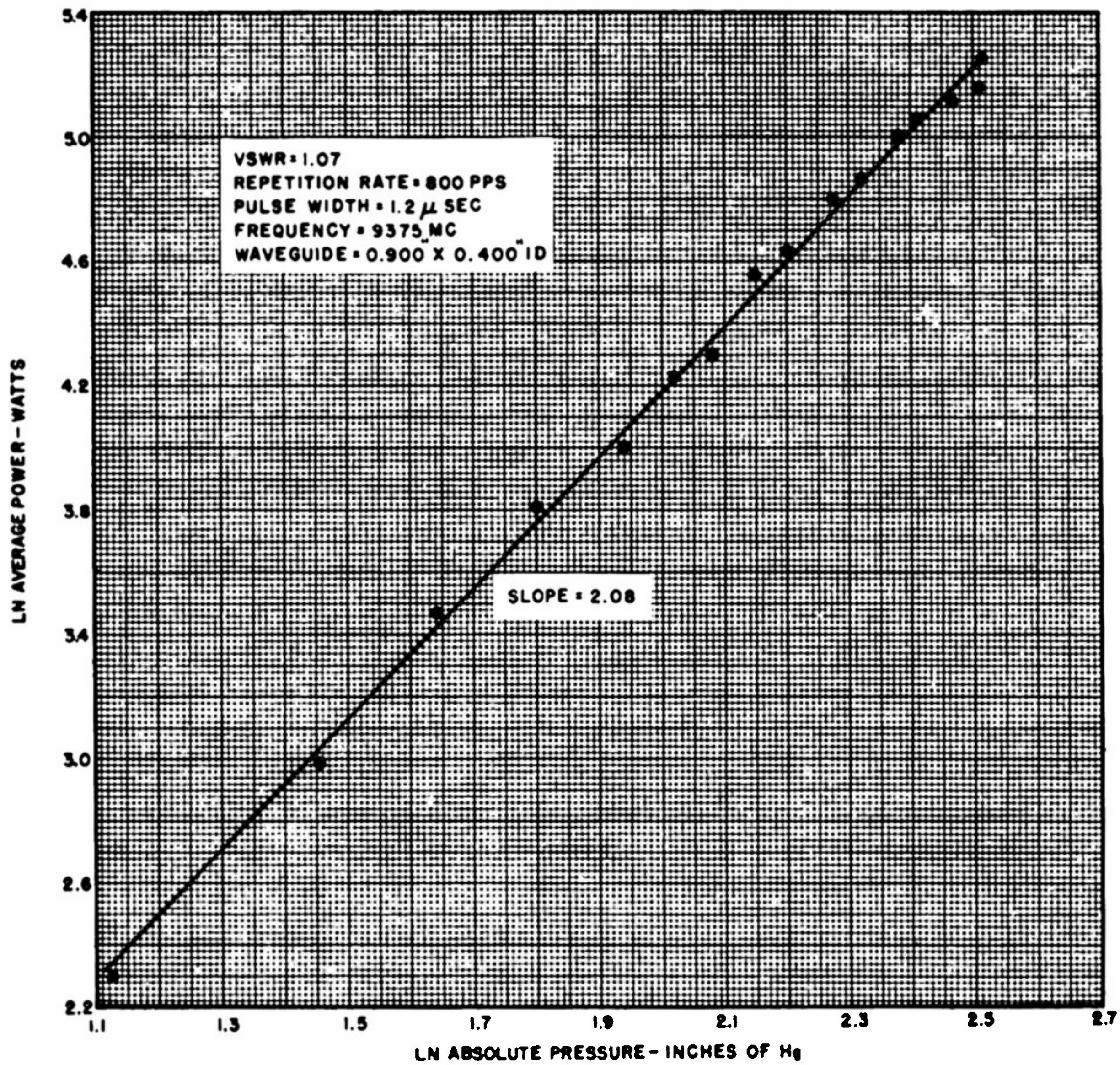

FIGURE 2
BREAKDOWN POWER vs. PRESSURE
WITH COBALT IN CONTACT WITH
TAPERED-WAVEGUIDE BREAKDOWN GAP

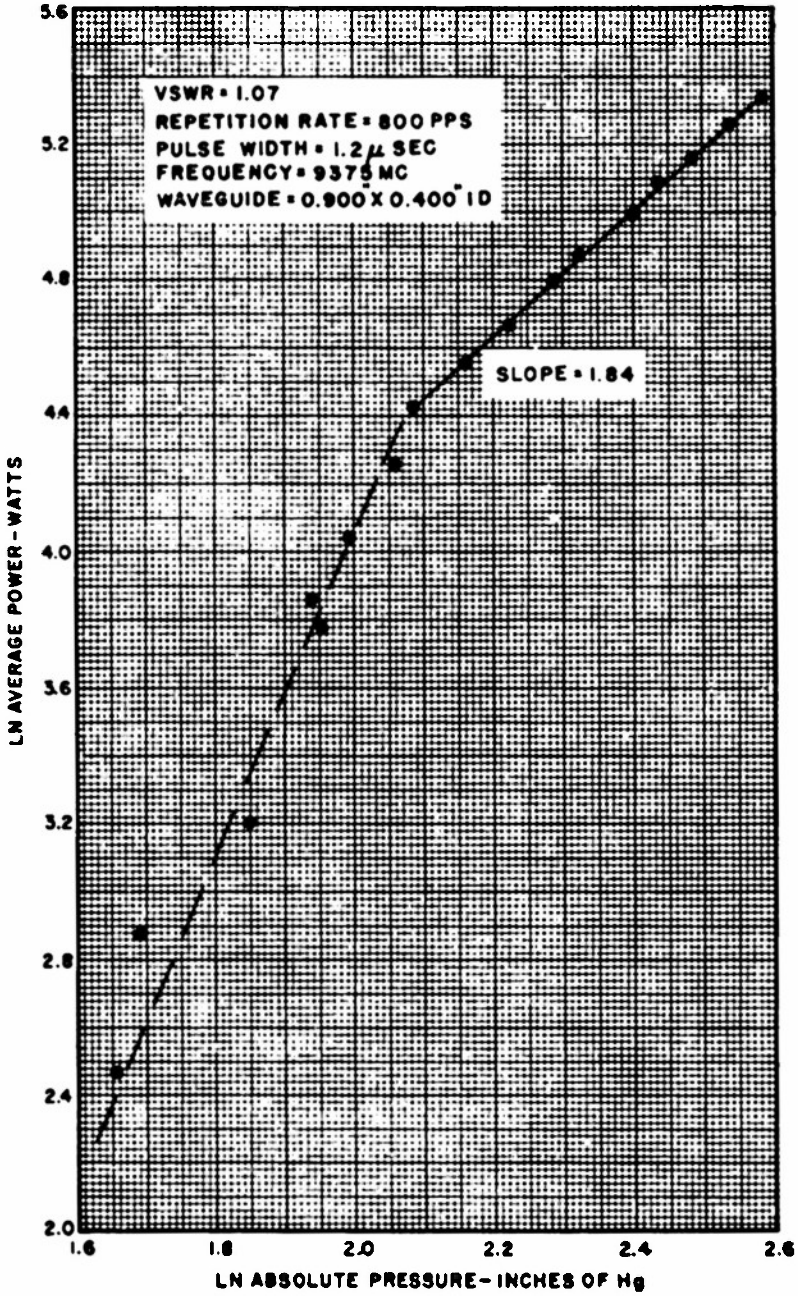

FIGURE 3

BREAKDOWN POWER vs. PRESSURE WITH COBALT 1" ABOVE TAPERED-WAVEGUIDE BREAKDOWN GAP

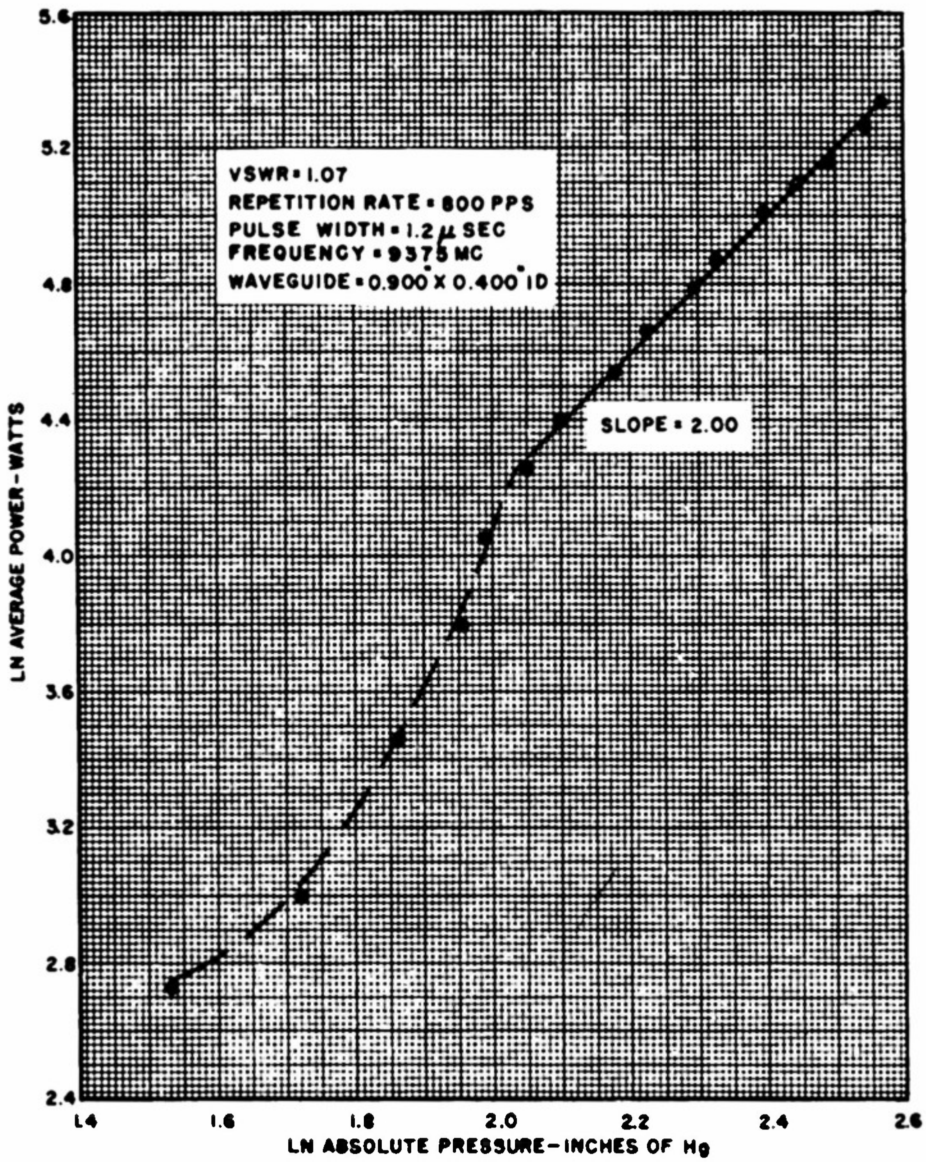

FIGURE 4

BREAKDOWN POWER vs. PRESSURE WITH COBALT 2" ABOVE TAPERED-WAVEGUIDE BREAKDOWN GAP

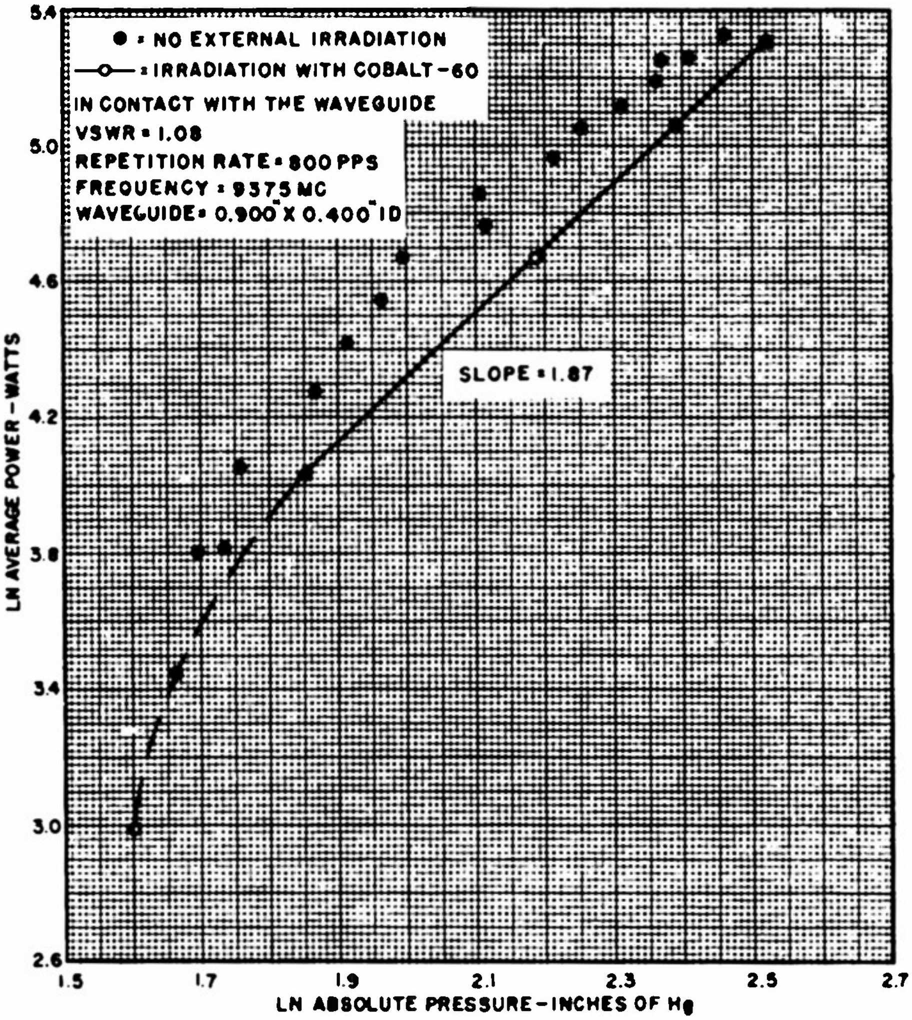

FIGURE 5
BREAKDOWN POWER vs. PRESSURE
FOR A PULSE WIDTH OF 1.2μ SEC

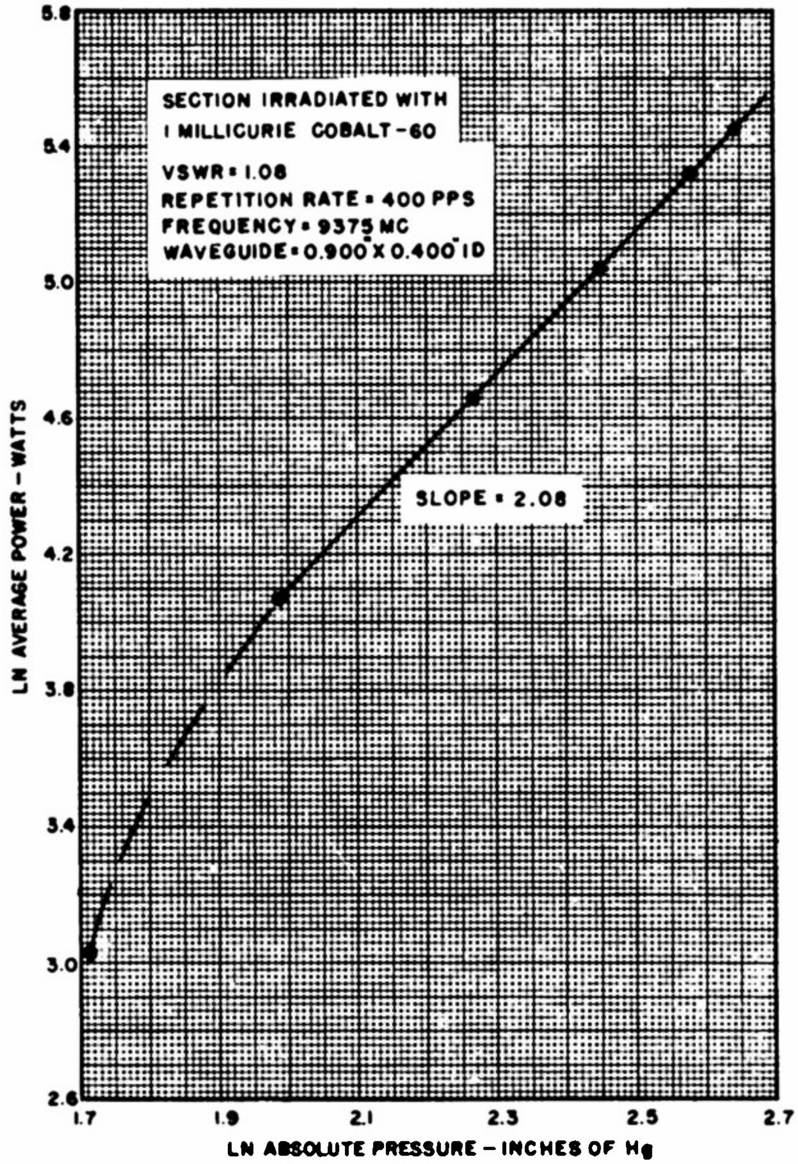

FIGURE 6
BREAKDOWN POWER vs. PRESSURE
FOR A PULSE WIDTH OF 2.35μ SEC

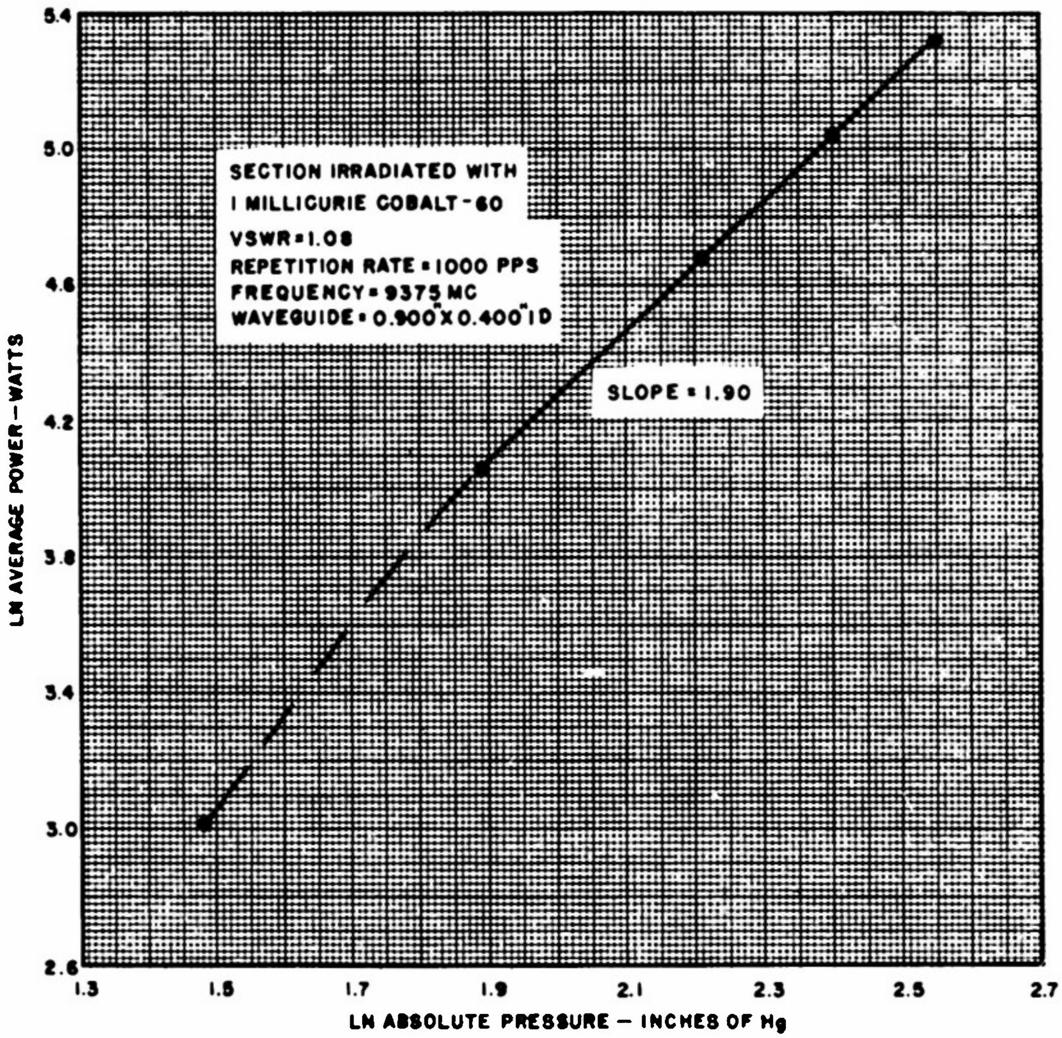

FIGURE 7
BREAKDOWN POWER vs. PRESSURE
FOR A PULSE WIDTH OF 0.8μ SEC

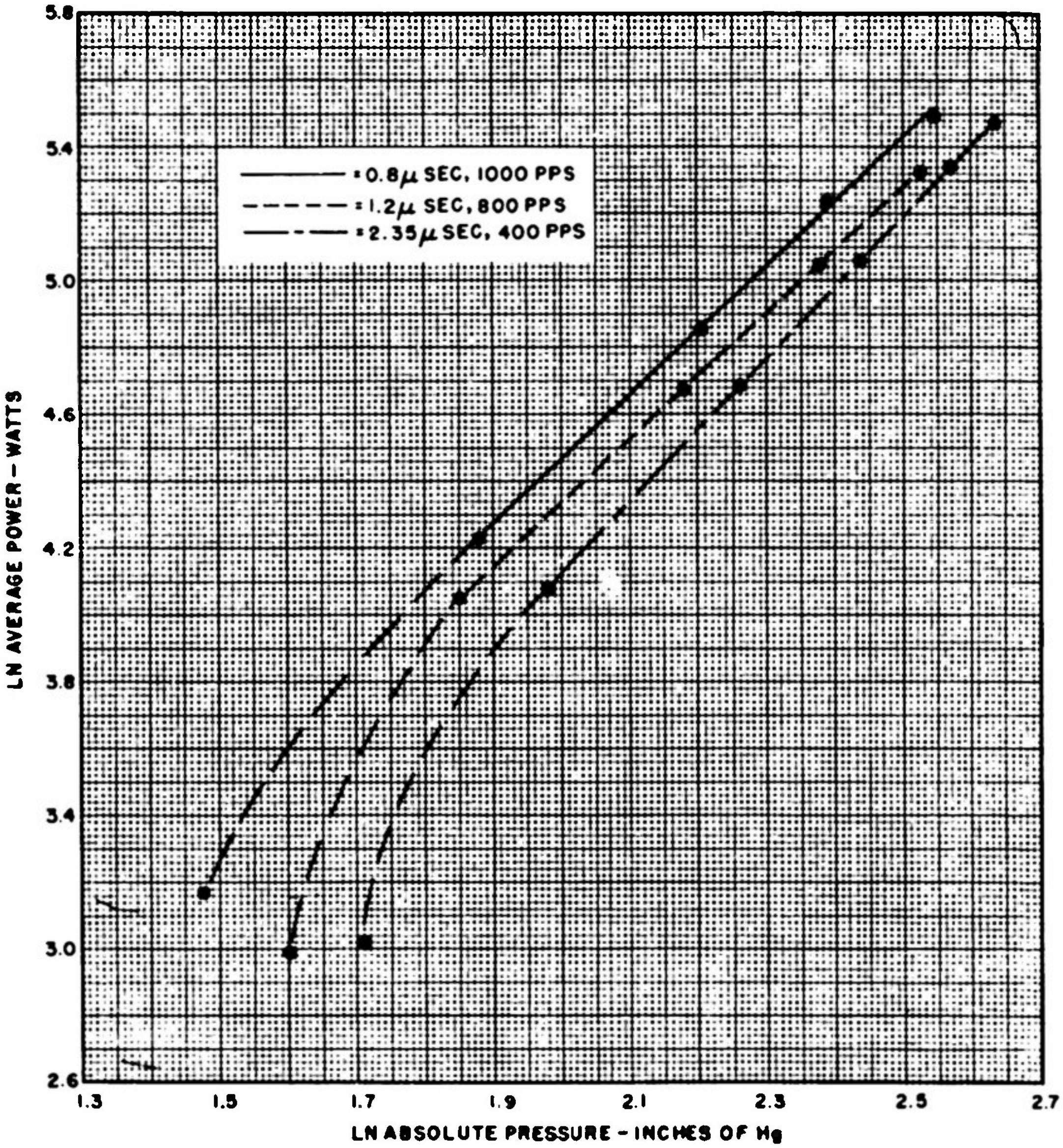

FIGURE 8
NORMALIZED CURVE FROM THE DATA
OF FIGURES 5, 6, AND 7